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Review

Deficit irrigation in tomato: Agronomical and physio-biochemical implications

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ABSTRACT

In present context and under foreseeing scenario of climate change, the declining of water allocation to agriculture due to increase of population and food demand has sensitized judicious use of available water in agriculture. Under such scenario, maximization of crop water productivity is more crucial than simple yield maximization – a target usually anticipated under irrigated condition. Deficit irrigation (DI) has been proposed as a valuable strategy of economizing water use, more particularly in water scarce arid and semi-arid regions. Available literature suggests that appropriate DI strategy may account for a significant amount of water saving with some improvement in fruit quality such as in tomato, one of the most nutritious and economic vegetables of global significance. In present review, varying aspects of DI in tomato are discussed: tactful (growth-stage/-period wise) implementation of DI strategies to attain satisfactory level of water saving without or with a minimum penalty on economic yield and quality; various morphological and physio-biochemical implications of DI in tomato plants relevance to conservative use of water; the integrated approach involving different agronomic practices with DI; and the future prospects of DI, and its combination with other approaches for sustainable tomato cultivation is also highlighted.

1. Introduction

The maximization of crop production had been prime motive of agricultural research in the twentieth century; however, in the recent past the focus has shifted towards optimum utilization of natural resources (Geerts and Raes, 2009). Water is one of the most critical resources for crop production, and agriculture is considered as major water consuming sector with ~70% of water use (FAO, 2011). In certain areas like arid and semi-arid regions in Asia, its share reaches up to 85% in agriculture (Ragab and Prodhomme, 2002). Major challenge to agriculture is to meet the projected demand of doubling the food production by 2050 (OECD, 2010), especially in a situation of declining water allocation to agriculture because of increasing demands from other sectors (Hatfield, 2015). Further, water is likely to assume more importance in the wake of the predicted rise in severity of erratic weather and drought due to climate change (Trenberth, 2011). Its shortage has already become critical in many parts of the world (Forouzani and Karami, 2011), especially in the areas where irrigation water has been over-exploited (Chai et al., 2016).

In a report from India, it is projected that with merely 10% increase in the present level of water use efficiency in irrigation projects, an additional 14 million hectare area can be brought under irrigation from the existing irrigation capacities (Swaminathan, 2006). Therefore, it becomes imperative to employ appropriate strategies that would entrust judicious use of limited and scarcely available water in agriculture for sustained crop production. Indeed, the maximization of crop water productivity may be more beneficial to the farmer than maximization of crop yield, particularly in water scarce areas (Pereira et al., 2002). Vegetables being sensitive to water deficit, availability of water can considerably influence crop yield and quality (Harmanto Salokhe et al., 2005). The present review specifically focuses on tomato, one of the most nutritious and economic vegetables of the world that is rich in vitamins, minerals and organic acids (Savić et al., 2008), and is also an important constituent of daily diet worldwide. Incidentally, it is also one of the most water demanding crops (Peet, 2005). Globally, tomato is cultivated over 4.78 million hectare lands with production of 177.04 million tons and productivity of 37.01 tons per hectare (FAO, 2016). Therefore, any aspect influencing tomato yield has attracted considerable interest among the researchers.

A yield response factor (k_y) between 0.99 and 1.05 in many studies on tomato reveals that its yield reduction is directly proportional to reduced water use. Therefore, there is a need to formulate strategies to enhance the water use efficiency (WUE) to strike a favorable balance between total production and water use. The most feasible way to

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enhance WUE is to opt for drought resistance cultivar and/ or practice efficient irrigation (Costa et al., 2007). However, development of drought resistant cultivars with good horticultural traits in vegetables have also been a great challenge as introgression of drought resistance traits into high yielding cultivar has been difficult because drought resistance is a complex and polygenic trait (Schwarz et al., 2010; Kumar et al., 2017).

Deficit irrigation (DI) has been found as a valuable alternative strategy of economizing water use under open field as well as protected conditions, particularly in arid and semi-arid regions (Fereres and Soriano, 2007; Geerts and Raes, 2009), where water is the most limiting factor for crop cultivation. It has been traditionally recommended under situations of recurrent water scarcity and drought spells to mitigate the adverse effects of water stress on crop yield (Kirda et al., 2004). There are many reports proposing DI as a viable strategy to produce more per unit of water applied in different crops, including tomato. However, there is a meager information and understanding about the level of deficit that could be imposed without incurring much loss in yield ensuring high WUE in tomato. The current review gives an overview of the strategies of DI followed in tomato to economize water use, their impact on marketable fruit yield and quality along with effect of integration of other agronomic practices. Mechanisms involved and future strategies are also discussed.

2. Deficit irrigation

DI is well recognized water saving strategy, achieved by deliberate application of sub-optimal amount of water which may or may not result in some yield reduction. It does not enhance growth and yield as such but by modifying plants' physiological processes it can influence efficiency of water use that would lead to considerable water saving. DI may also result in improvement of fruit quality, reduction of production cost, besides minimization of the pollution of ground water due to reduced leaching of nutrients and pesticides with less water application (Pulupol et al., 1996; Nangare et al., 2016).

As illustrated in Fig. 1, there are broadly three main strategies of DI in practice:1) conventional or classic deficit irrigation (CDI), 2) regulated deficit irrigation (RDI), and 3) partial root zone drying (PRD). In CDI, water is supplied at levels below full crop evapo-transpiration (ETc) across all the growth stages e.g., 80, 60, 40% of ETc or CPE of normal irrigation (100% ETc or CPE); if these alone or in combination are implemented considering the sensitivity at different growth stages in regulated manner, it is termed as regulated deficit irrigation (RDI); scheduling water application in such a way that would result in certain degree of root zone drying, intermittently (alternate, APRD) or continuously (fixed, FPRD) is classified as PRD. The overall objective of any DI practice mentioned thereof is to save water either by reducing amount of water in each irrigation or by reducing number of irrigations with minimum loss in quality yield.

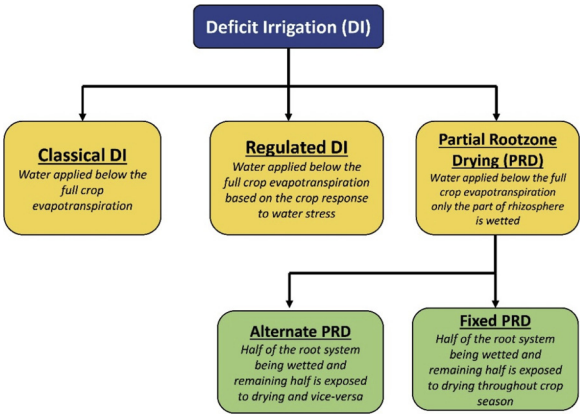
Deficit Irrigation (DI)
Classical DI
Water applied below the full crop evapotranspiration
Regulated DI
Water applied below the full crop evapotranspiration based on the crop response to water stress
Partial Rootzone Drying (PRD)
Water applied below the full crop evapotranspiration only the part of rhizosphere is wetted
Alternate PRD
Half of the root system being wetted and remaining half is exposed to drying and vice-versa
Fixed PRD
Half of the root system being wetted and remaining half is exposed to drying throughout crop season

Fig. 1. Schematic representation of different methods of deficit irrigation in tomato.

3. Effect of DI on WUE, fruit yield and quality

The appropriate DI strategy would be such that would entrust to maximize the efficiency of per unit water applied and having potential to deliver promising crop yields with no adverse effects on quality of produce (Ćosić et al., 2015). The acceptable level of DI in most of the studies has consistently increased WUE of tomato crop with negligible to marginal yield reduction (Kirda et al., 2004; Patanè et al., 2011; Kuscu et al., 2014; Bahadur et al., 2015). The promising effect of DI in many studies was the consistent improvement in tomato fruit quality attributes (Patanè and Cosentino, 2010; Zegbe-Domiguze et al., 2003; Kirda et al., 2004; Harmanto Salokhe et al., 2005). Available research on these aspects in tomato is relatively less for open field condition than greenhouse production (Kuscu et al., 2014), even though the prevalence of soil moisture deficit is more frequent in open field production system.

It is widely reported that the sensitivity to soil moisture deficit can vary with crop phenological stages, hence imposition of DI during non-critical stages may be more beneficial with respect to the enhancement of WUE (Nangare et al., 2016). The water-sensitive stage(s) may vary with crop species. However, flowering and fruit setting stages are reportedly most sensitive to WD in tomato (Kuscu et al., 2014). Hence, imposition of DI particularly during these stages may lead to a considerable yield reduction and WUE (Harmanto Salokhe et al., 2005). Besides the timing or stage of irrigation, the level of DI may also affect yield and quality of tomato, thereby influencing the WUE (Wang et al., 2011). Suppose, vegetative and fruit ripening stages are less sensitive to DI but at what WD (whether 80, 70, 60 or 50% of ETc) has to be imposed is of utmost important. Therefore, considering the above facts, it is imperative to choose an appropriate DI schedule to achieve high WUE (Ngouajio et al., 2007). The schematic representation of the general effect of DI on phenological stages of tomato is depicted in Fig. 2.

The potential of DI to enhance WUE in tomato has been widely documented (Costa et al., 2007; Fereres and Soriano, 2007; Nangare et al., 2016). However, a careful implementation of DI is required as plants subjected beyond a certain level of water deficit may show adverse effect on marketable fruit yield (Kuscu et al., 2014; Nangare et al., 2016). The results of a study reveal that a gain of 7–10% additional yield and 10–27% higher marketable yield was attained in PRD over conventional DI treatments, even when the two systems received a similar amount of water (Kirda et al., 2004).

In a typical semi-arid Mediterranean environment, tomato (cv. Brigade) reflected 46.2% saving of water without losing any marketable yield when irrigation was given at 50% ETc level throughout the growing season (Patanè et al., 2011). On the contrary, Lahoz et al. (2016) also registered considerable amount of water saving (28.2%) under DI (75% ETc), but fruit yield was also reduced by 16.4% as compared to control (100% ETc). Thus, effective DI requires knowledge related to the interaction between water availability and crop growth stage making it difficult to practice in field condition. On the contrary, the concept of PRD often practiced through alternate furrow irrigation is relatively easy to apply in a field.

Two partial root zone irrigation (PRI) schedule i.e., alternate partial root-zone irrigation (APRI) and fixed partial root-zone irrigation (FPRI) when compared with conventional irrigation (CI) in a pot experiment (Yang et al., 2012) revealed that APRI was more promising as it enhanced fruit yield and WUE more than FPRI.

Application of DI at various phenological stages in tomato (cv. *Shasta*) demonstrates that a combination of full irrigation (100% ETc) until beginning of fruit ripening and later termination of irrigation was optimum to achieve a considerable amount of water saving (33%) and high irrigation WUE (42%) with only a marginal loss in fruit yield (5%) compared to application of full irrigation throughout growing period (Kuscu et al., 2014). A severe yield reduction was noticed when DI was

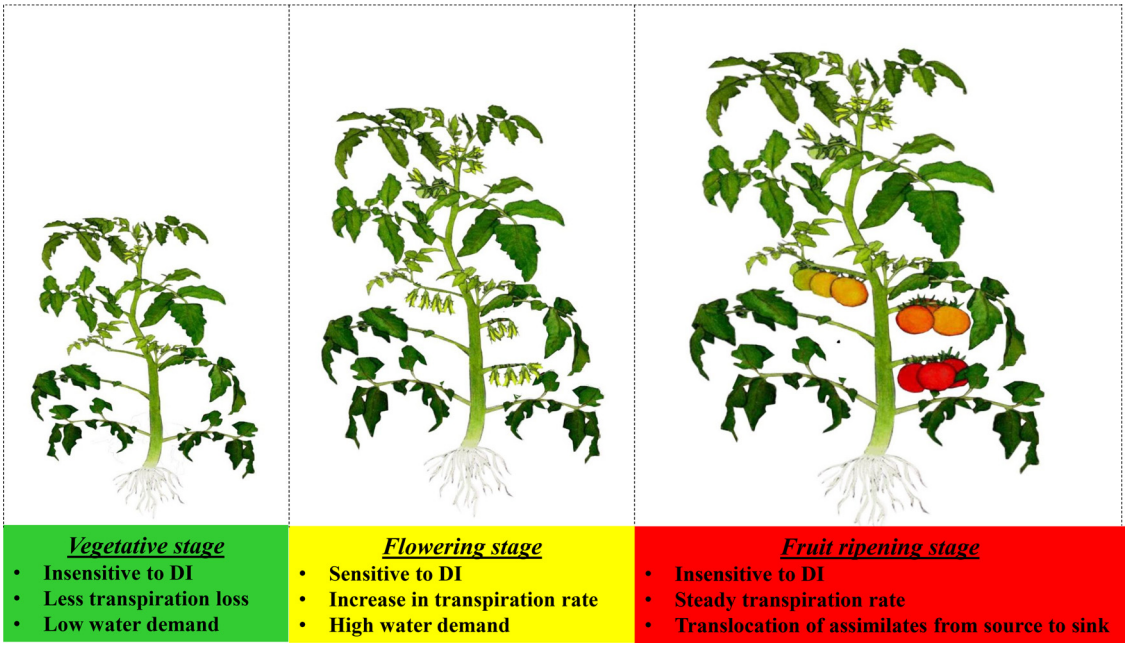

Fig. 2. Illustration of phenological stages of tomato and their sensitivity response to deficit irrigation.

applied at any of the critical stages of tomato plant. Thus, DI scheduling during vegetative and fruit ripening stage under limited water condition is more viable solution (Kuscu et al., 2014). Furthermore, Nangare et al. (2016) have also recorded a significant improvement in water saving when DI was imposed during vegetative stage. These researchers have found that DI at 0.8ETc was highly beneficial for obtaining the highest water productivity (19.2 kg m^{-3}), without having any adverse effect on marketable fruit yield of tomato (76 t ha^{-1}). Further, growth stage-wise application of DI has rather increased the marketable fruit yield, the highest (81 t ha^{-1}) being recorded when plants were irrigated at 0.6 ETc during vegetative growth stage (44 days) followed by full irrigation (1.0 ETc) throughout cropping period with water productivity of 19.1 kg m^{-3}. From their study, Nangare et al. (2016) concluded that high water productivity with sustained fruit yield of and good fruit quality could be achieved with RDI at 0.8 ETc throughout crop period + 0.6 ETc during vegetative stage.

In a time-based DI scheduling system, irrigation at 20 days interval did not significantly reduce fruit number and yield over irrigation at 10 days interval even though it amounted to 36% water saving and high WUE in Inceptisol at Varanasi during *rabi* season tomato (Bahadur et al., 2015).

The possible consequences of DI on fruit yield and quality may be different. Earliness in fruit maturity (by one week) was evident, especially in PRD (Zegbe-Domiguze et al., 2003). Majority of reports are in support of its positive effect on tomato fruit quality attributes, especially the soluble solids contents which presumably occurred as a consequence of reduced transport of water to the fruits concomitant to increased accumulation of photo-assimilates under WD condition (Plaut et al., 2004; Zegbe et al., 2006; Nangare et al., 2016). The accumulation of assimilates in fruits under water stress may also occur due to the reduced fruit size and low dilution as a consequence of decreased water content of fruit (Nangare et al., 2016). The reduced rate of water transport to the tomato fruit and increased rate of dry matter accumulation under WD was also noticed by Plaut et al. (2004). These justify the widely reported inverse relationship between yield and fruit solid contents (Garcia and Barrett, 2006; Helyes et al., 2012; Kuscu et al., 2014). The reduced fruit size, which is likely to occur in DI, was also inversely related to TSS or water soluble dry matter e.g., sugars and organic acids and the overall flavor determining attributes of tomato fruits (Ho, 1996; Bertin et al., 2000; Kirda et al., 2004). The decrease in fruit number and fruit water content was reported under DI or PRD, whereas the enhancement of fruit soluble solids content (SSC) was invariably associated with PRD. Nangare et al. (2016) have also observed an increasing trend for the quality parameters like hardness, TSS, ascorbic acid, acidity and colour (lycopene) at the expense of marginal decrease in fruit size with increase of WD level. Under optimized level of DI, a satisfactory level of SSC (Kuscu et al., 2014) and improvement in contents of TSS, vitamin C and acidity in tomato fruit were also reported (Patanè et al., 2011).

Unlike the common response on increase in SSC or TSS content, the response of DI was inconsistent for the content of lycopene, an associated fruit colour factor with important antioxidant properties. Moreover, its concentration was also influenced by a cultivar and growing season (Favati et al., 2009). An increase in lycopene content (13.9 mg/100 g) with high colour index value (44.6) of tomato fruit was observed in DI at 0.6ETc (Kumar et al., 2015). However, while comparing the response of four tomato varieties with variation in intrinsic lycopene content, Lahoz et al. (2016) did not observe any variation in lycopene content among the varieties maintained under irrigation at 75% ET. Interestingly, the WD level enhanced TSS content, fruit colour (Hunter a/b ratio) and most of the aroma volatiles indicative of quality parameters particularly in high lycopene cultivars. Others have also reported an increase in concentration of aroma compounds (Veit-Köhler et al., 1999) and fruit colour under WD (Garcia and Barrett, 2006). Djurovic et al. (2016) noted the highest WUE (49.8 kg m^{-3}) with increase in organic acid content and anti-oxidant activity under DI of 50% ETc in tomato. Growth stage specific DI in tomato studied by Kumar et al. (2015) suggest that critical deficit irrigation (CDI) or withholding irrigation during fruiting stage can improve fruit quality and functional food characteristics of tomato fruits. Compared to control, they observed that CDI (0.6 ET) increased fruit color (a/b* ratio) by 82% and vitamin C content by 70%, whereas the corresponding increase of these parameters due to withholding of irrigation at fruit development stage was 52% and 16%, besides recording of high lycopene content (10.2 mg/100 g). DI at fruiting stage also improved total phenolics and flavonoids compounds, and antioxidant as well as enzyme activities in tomato fruits (Kumar et al., 2015). Thus, DI of 0.6 ET at fruiting stage not only saved water but improved the quality of tomato fruit. The summary of perfromance of tomato plants for fruit yield, quality and WUE studied under DI at different locations is presented in Table 1.

Table 1
Agronomic performance of tomato plants under different conditions of deficit irrigation.

Irrigation regimes/Treatments	Best treatment in ETc (%)	Agronomical characteristics		Location & Reference
		Yield and Quality	WUE / Water saving (%)	
Classical DI throughout season 100, 125 and 75% ETc	75	16.4% reduction in marketable yield but enhanced TSS, lycopene and aroma	28.1 and 28.3 % reduced compare to standard	Navarre, Spain (Lahoz et al., 2016)
Classical DI throughout season 100 and 50% ETc	50%	Increase in organic acid and anti-oxidant activity	49.8 kg m^{-3}	Belgrade, Serbia (Djurovic et al., 2016)
Irrigation at 40, 50, 60, 70, 80 and 100% ETc	80% ETc	Highest yield and increase in SSC and vitamin C	[a]27.2 and 29.4 kg m^{-3}	Inner Mongolia, China (Zhang et al., 2017)
Irrigation at 0, 50, 100 and 100-50% ETc	100-50% ETc	No significant difference in yield in comparison to 100% ETc	[a,b]1.15 and 0.63 kg m^{-3}	Basilicata, Italy (Favati et al., 2009)
Irrigation at 50, 75 and 100% Ep	50% Ep	Decrease in yield with significant saving in irrigation water	23.9 and 17 kg m^{-3} for (TY-DANA and GS12 cultivars respectively)	Jordan Valley, Jordan (Mahadeen et al., 2011)
Classical DI throughout season 100-50% ETc restoration up to fruit maturity 100% ETc restoration up to flowering then 50% ETc	50% restoration throughout season	No loss in marketable yield & enhanced TSS, acidity and Vitamin C	[a]17.45 and 22.99 kg m^{-3}	Sicily, Italy (Patanè et al., 2011)
Regulated DI throughout season (0.6, 0.8, 1.0xETc) FI except stage specific deficit of 0.6xETc at vegetative (VS), flowering (FL), fruiting (FR), (VS + FL), (VS + FR), (FL + FR) FI except interrupted irrigation (15 days) during vegetative, flowering and fruiting	Regulated DI at 0.8xETc	Highest marketable yield 76 tha^{-1} and improvement in fruit quality parameters	19.2 kg m^{-3}	Baramati, India (Nangare et al., 2016)
FI at 100% ETc with 3-day intervals with other treatments, irrigation was not applied during the vegetative, flowering, yield formation or ripening stages or during combinations of these stages.	FI until the beginning of ripening and termination till harvest	Acceptable SSC with marginal yield reduction (5%)	33% water saving and 42% increase in IWUE	Bursa province, Turkey (Kuscu et al., 2014)
Partial root drying (PRD), APRD, FPRD and Conventional irrigation	APRD (levels)	Enhanced fruit yield & vitamin C, SSC and sugar: acid ratio	36.6 kg m^{-3}	Shenyang, China (Yang et al., 2012)

Ep: Pan evaporation; FI: full irrigation; IWUE: Irrigation water use efficiency; TSS: Total soluble solids; SSC: Soluble solid content.
[a] Two season data.
[b] WUE is on the basis of dry fruit yield.

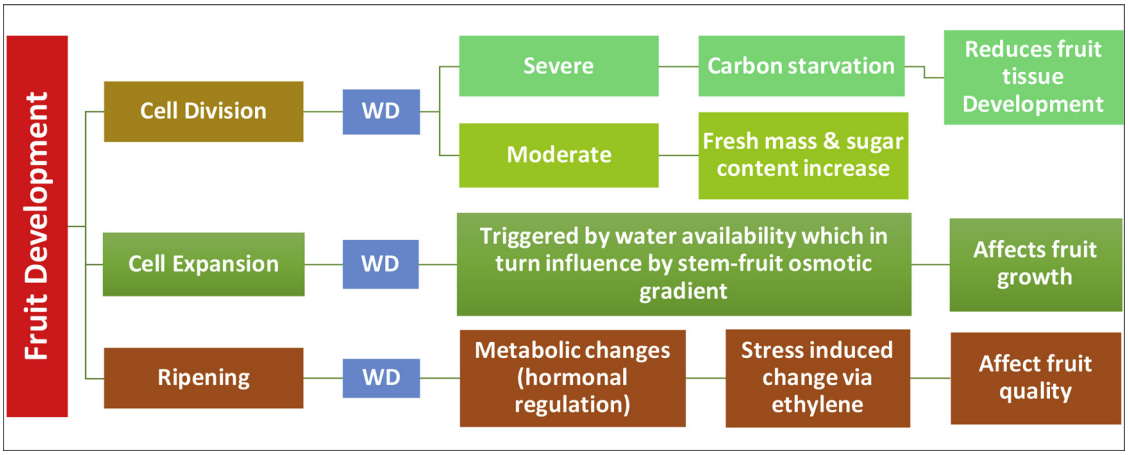

Fig. 3. Effect of DI on sub-phases of fruit development affects fruits size and quality.

Review of literature also reveals that during the different sub-phases of fruit development water deficit significantly influences fruit size and quality as depicted in Fig. 3.

4. Deficit irrigation induced changes in tomato plant

4.1. Change in plants morphometric characters

Water is essential for plant growth and its deficit would impact plant growth and production, depending on severity and duration of water deficit, besides growth stage. It is well recognized that shoot and root growth have direct influence on crop yield under optimal growth environment, whereas their response can vary under WD condition. Shoot growth invariably decreases, whereas root growth increases till an acceptable level of WD leading to improvement of crop WUE (Kumar et al., 2017). Furthermore, the decrease in shoot growth under DI may not necessarily result in reduction in yield. In contrast, the root system plays a significant role in formulation of appropriate DI strategy to attain an acceptable level of WUE. The root system characteristics such as root-length, -biomass, -density, -volume and root to shoot ratio may provide sustenance to yield.

The structural change in roots possibly occurred due to reallocation of assimilates from shoot to root by plants under water stress (Xu et al., 2015). High root:shoot ratio may not necessarily lead to water stress tolerance as demonstrated by Suchoff et al. (2017). These researchers did not find relation between water stress tolerance and root:shoot ratio as tomato plants with two different rootstocks reflected different sensitivity response to water stress in spite of having similar shoot and root dry mass. Hence, the role of other root morphometric traits is also crucial. For instance, root expansion to deeper soil layer has been considered to be the primary manifestation of WD in plants to extract water and nutrients (Koevoets et al., 2016; Kumar et al., 2017). The improved performance of tomato plant was related to increased root length with high proportion of thin roots rather than root:shoot ratio (Suchoff et al., 2017). The highest marketable fruit yield as well as water productivity in RDI treatment (1.0 ETc for whole period except 0.6 ETc at vegetative stage) was possible due to increased root growth (root -length and -dry weight) that favored water and nutrients uptake and their supply to the growing shoots (Nangare et al., 2016). Also, better performance of APRI on growth, production and physiological efficiency in comparison to FPRI was partly related to better root activity that occurred due to alternate wetting and drying of soil, whereas roots experiencing continuous WD resulted in restricted root growth in FPRI (Yang et al., 2012).

Shoot morphological characteristics including leaf area, stomatal density, and pubescence on the leaves and stem may also contribute to water saving by restricting water loss through transpiration. Lesser the leaf area and stomatal density more will be water saving (Xu and Zhou, 2008). The response of WD can also vary with phenological stages of plants; e.g., flowering and fruiting stages are highly sensitive to water stress in tomato (Nangare et al., 2016) as water shortage particularly at these critical stages results in a significant flower abortion (Pulupol et al., 1996; Zegbe et al., 2006). Avoiding the critical stages in formulating the DI strategies were advantageous for WUE and fruit quality with or without yield increase (Nangare et al., 2016). Therefore, DI scheduling at non-sensitive stages such as vegetative and fruit ripening stages can be a gainful strategy to obtain favorable results with respect to WUE.

4.2. Changes in physiological and biochemical processes

An intrinsic balance among transpiration, CO_2 and water uptake is required for optimum plant growth. These are dependent on stomatal characteristics and physiology, besides the root architecture (discussed in previous the section). Root physiology also plays critical role in maintaining this balance (Weng, 2000). Although, WD reduces leaf area and plant growth, increase in WUE can be achieved by decrease in water loss through transpiration from reduced surface area of plant (Xu and Zhou, 2008). Under condition of a constant air vapor pressure deficit, the relationship between stomatal conductance and transpiration rate is linear, whereas the non-linear relationship is prevalent between stomatal conductance and photosynthetic rate which implies lower stomatal aperture caused improvement in WUE (Chaves et al., 2002). FPRI exhibited less iWUE (instaneous water use efficiency) than APRI owing to more drop in rate of photosynthesis and transpiration presumably due to prolonged drought experience by half root-zone of FPRI roots (Yang et al., 2012). These researchers have also observed higher root activity under APRI where water stressed roots reflected compensation effect on root growth after rewatering that helped to sustain root activity (Yang et al., 2012).

Nangare et al. (2016) observed no distinct response of different irrigation levels (DI) on photosynthetic assimilation rate (PAR), water vapour conductance (WVC), transpiration rate and iWUE at vegetative stage, whereas at flowering and fruiting stages DI influenced these parameters. High PAR, transpiration and WVC was observed at 1.0 ETc followed by DI at 0.6 ETc. The increased iWUE in tomato plant was associated with PRI induced partial stomatal closure (Pazzagli et al., 2016) that could also lead to a decrease in leaf stomatal conductance as a response of water stress induced increased root-to-shoot chemical signaling (i.e., ABA) under moderate moisture deficit condition (Liu et al., 2006b). The regulatory effect of ABA in plant water use has also been explained in water stressed tomato plants (Dodd et al., 2000). Bahadur et al. (2015) have observed no significant change in fruit yield when crop was irrigated at 20 days interval as compared to normal 10

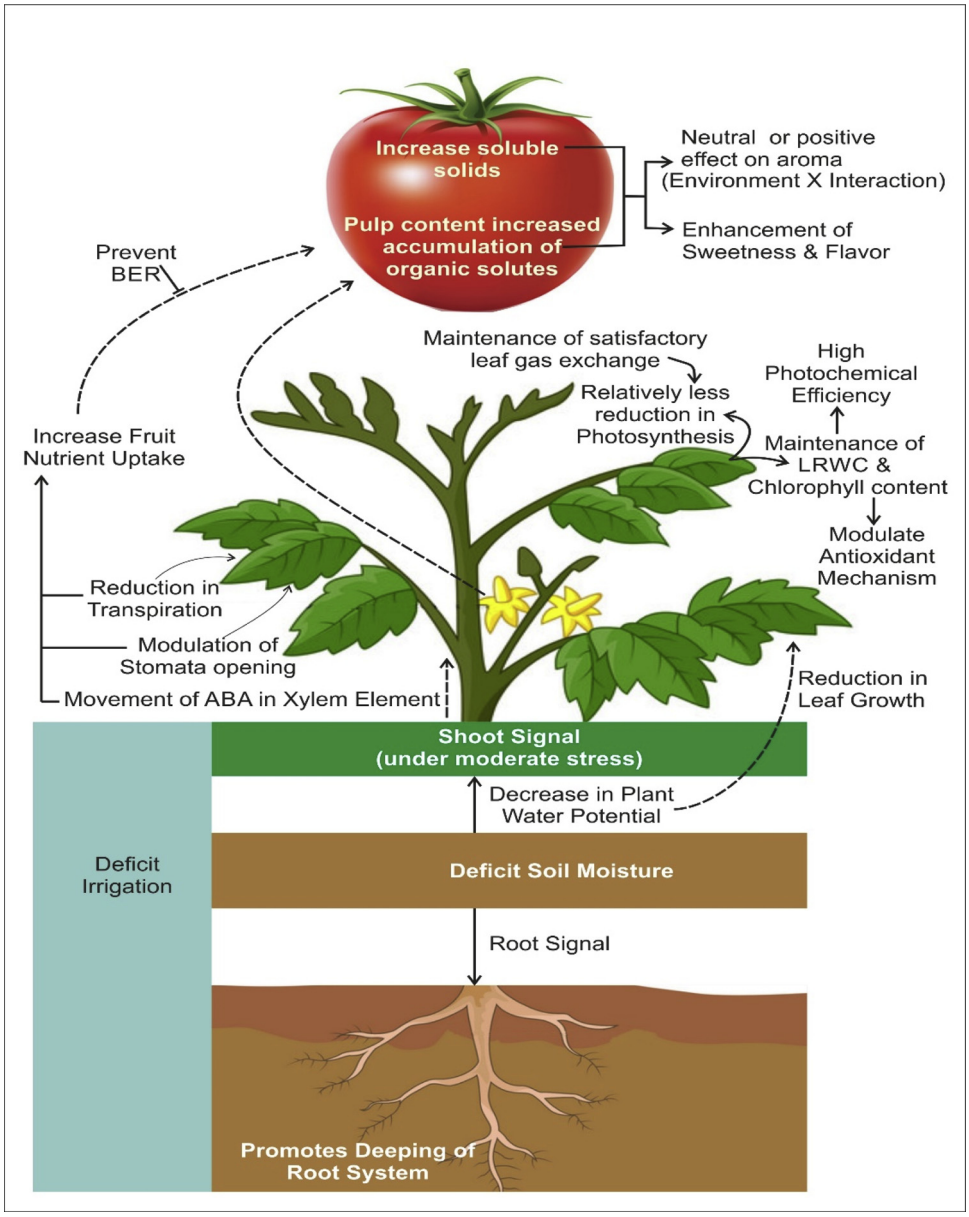
Increase soluble solids
Pulp content increased accumulation of organic solutes
Neutral or positive effect on aroma (Environment X Interaction)
Enhancement of Sweetness & Flavor
Prevent BER
Maintenance of satisfactory leaf gas exchange
Relatively less reduction in Photosynthesis
High Photochemical Efficiency
Maintenance of LRWC & Chlorophyll content
Modulate Antioxidant Mechanism
Increase Fruit Nutrient Uptake
Reduction in Transpiration
Modulation of Stomata opening
Movement of ABA in Xylem Element
Reduction in Leaf Growth
Shoot Signal (under moderate stress)
Decrease in Plant Water Potential
Deficit Irrigation
Deficit Soil Moisture
Root Signal
Promotes Deeping of Root System

Fig. 4. General response at physiological plane caused by deficit irrigation in tomato fruit.

days interval, but WD for prolonged period (another 10 days i.e. 30 days interval) significantly reduced leaf area, relative water content, chlorophyll index and Fv/Fm ratio. However, the activities of gas exchange parameters such as stomatal conductance and rate of photosynthesis and transpiration sustained, that consequently led to increase in WUE. The underlying mechanisms possible under DI reported to bring about changes in root (expansion of root system to acquire more water and nutrients, phytohormones), shoot (reduced plant growth and leaf area), and physio-biochemical processes including relatively less reduction in photosynthesis than transpiration, better osmo-regulation, higher antioxidant activity, etc as depicted in Fig. 4.

Enhancement of WUE under DI occurred due to decrease in transpiration caused by enhanced signal transduction network of guard cell, less decrease in photosynthesis to transpiration rate, and reduced evaporative water loss from soil surface, particularly in PRD (Chai et al., 2016). RDI promotes plants to reduce leaf water content or leaf water potential substantially (Liu et al., 2006a; Pérez-Pastor et al., 2014) that acts as a hydraulic signal (along with chemical signals discussed earlier) triggering partial closure of stomata and reduced leaf area expansion (Shahnazari et al., 2007).

Partial root drying (PRD) may result in drying of superficial roots. This induces stomtal closure (Liu et al., 2006b; Sobeih et al., 2004) in response to chemical signals many a times before there is any detectable change in leaf water potential (Davies and Zhang, 1991). Less water applied so as to facilitate PRD also results in partial closure of stomata. Consequently water loss through transpiration is restricted. However, there is minimal adverse effect on photosynthesis (de Souza et al., 2005; Liu et al., 2004). Literaure reports that PRD often results in better root growth and activity leading to more efficient utilization of soil water primarily through improved root : shoot ratio (Li et al., 2014; Wang et al., 2012; Yang et al., 2012)

Thus, theoretically, RDI and PRD may trigger different water-deficit stress mechanisms and, consequently, different plant physiological and growth responses. RDI is advantageous when suitably managed because the application of a mild plant WD can decrease vegetative vigour and possibly improve the partitioning of carbohydrates to reproductive structures (Chalmers et al., 1986; Jones, 2004). RWC and leaf water potential were at par control in PRD as compared to RDI even when

they received the same amount of water. They, however, adversely influenced growth and transpiration. Carbon assimilation, expressed as Rubisco activity, may have been inhibited less in PRD than in RDI plants

On the contrary, subsurface irrigation usually induces osmotic adjustment, increases leaf turgor potential, and consequently enhances photosynthetic activities (Xu et al., 2011b). In this case, a false signal of WD is transduced inside the cell, where it induces xerophyto-physiological regulation with internal adjustment from the gene to physiological plane (Xu et al., 2009, 2011a, 2012).

It is well known that response to a particular level of WD varies with the growth stage of the exposed plants, besides climatic conditions, crop species, cultivars, and agronomic management practices followed in crop raising. At low ambient temperature, plastic covers on crops benefits through reduced soil evaporation, soil erosion, and rise in topsoil temperature thereby leading to improved nutrient availability (Gan et al., 2013). This is likely to be beneficial under water stress situation e.g., plants supplemented with 60 kg Nha^{-1} were reported to adjust osmotically and maintain high plant water potential and consequently register less reduction of stomatal conductance under water stress. Such an interactive response of DI and fertilization has also been reported wherein foliar application of calcium (0.8%) stimulated the benefit of APRI response by further enhancement of WUE (36.6 kg m^{-3}). Further, it is envisaged that deficit irrigation of mild intensity promotes root growth thereby influencing nutrient acquisition positively (Liu et al., 2011; Li et al., 2014). Further, drying and wetting cycles under RDI may also lead to more mineralization of soil organic N and subsequently more N availability compared to regular irrigation. Relative concentration of different inorganic ions in various compartments of leaves also exercises control over stomatal regulation and subsequent transpirational water loss especially under water stress conditions (Sobeih et al., 2004). Roots can also sense soil drying and produce chemical signals (i.e. increased ABA concentration, xylem sap pH or apoplastic pH) that are transmitted to the shoots and account for the reduction of stomatal conductance and leaf growth (Loveys, 1984; Wilkinson et al., 1998; Gowing et al., 1990; Zhang and Davies, 1990; Gollan et al., 1992; Bacon et al., 1998; Sobeih et al., 2004).

It is pertinent to highlight here that one of the main reasons of decrease in marketable fruit yield of tomato under WD condition is also incidence of blossom end rot (BER) that is mainly caused due to calcium deficiency in plants and particularly in the developing fruits. Restriction in movement of calcium from soil to plant and subsequently to fruits under WD condition (Saure, 2001; Marouelli et al., 2004) lead to BER. Studies have shown that soil WD during reproductive stage such as from first truss to fruit set (Zegbe et al., 2006) or during fruit development and ripening (Kuscu et al., 2014) have also severely hampered marketable fruit yield of tomato, mainly caused by high incidence of blossom-end rot (Zegbe et al., 2006). Therefore, considering the facts related to BER incidence and also its predispose factors such as use of cultivar and growing conditions including soil quality, fertilization, soil and air temperatures and so on, careful implementation of DI programmes to be followed to harness good response on quality yield.

5. Integration of other cultural interventions

Numerous reports have indicated that DI integrated with cultural practices have beneficial response on water use as well as on crop production traits. Such integration could be more effective for the enhancement of crop WUE of tomato plants also. Unlike widely studied response of sole application of DI, a few reports are there on the integrated use of DI with some agronomic practices. The strategies to cope with future water issue may be developed by integrating some of these including associations between roots and soil microorganisms.

5.1. Growth promoting microorganisms and chemical compounds

The co-inoculation of tomato plants with some microorganisms have resulted favorable response under WD condition. Arbuscular mycorrhizae (AM) were most potent microorganism that provided beneficial effect on yield and WUE of tomato plants as a result of increased uptake of some of the nutrient elements (e.g. nitrogen and phosphorus) during season-long deficit irrigation (Bowles et al., 2016). These authors also found increase in tomato red fruit biomass (both fresh and dry) by ~25% in AM inoculated plants under field conditions in both the control and deficit irrigation regimes. Giuliani et al. (2018) integrated deficit irrigation (50%) with strobilurin (agricultural fungicide) and found it to be associated with lower stomata conductance, maintaining higher assimilation rate, leading to an increase in WUE (25.9 g l^{-1}) on total yield basis in genotype IT-22/025 of tomato. Pal et al. (2016) suggested that paclobutrazol application can improve tolerance in tomato plants and lead to significant improvement in WUE by changing shoot and root characteristics, and altering physiological, biochemical and molecular plant processes under DI. AbdAllah et al. (2018) compared the effect of different anti-transpirants and found that the use of fluvic acid, a metabolic anti-transpirants, at the rate of 0.2% increased WUE by 33.5% (14.80 kg m^3) and there was further reduction in water requirement by 28%, because its application substantially ameliorated the adversities of drought by sustaining CO_2 assimilation rate (P-net). This suggest that integrating different agronomic practices along with deficit irrigation can further enhance WUE.

5.2. Vegetable grafting

Grafting has become an integral part of hi-tech vegetable production system in many countries owing to its effectiveness to tailor plants to overcome certain biotic and abiotic stresses, including water stress. In fact, grafting enables to exploit the benefit of characteristically strong root system of hardy genotypes to enhance the efficiency of commercial cultivars under challenged external root environments through physical reunion achieved by surgical means (Kumar et al., 2017).

Research findings revealed that with the use of appropriate rootstocks, grafting can be instrumental in enhancing tomato production under DI. Al-Harbi et al. (2017) and Ibrahim et al. (2014) have found a positive response of grafting (onto 'Unifort' rootstock) on vegetative growth (shoot fresh weight, leaf area, leaf dry weight) and yield. Grafted tomato plants produced higher mean fruit weight and number of fruits per plant and finally total yield compared to non-grafted plants, irrespective of water supply (Fernandez-Garcia et al., 2004). The grafting effect was more pronounced under high level of water deficit with an average increase in total fruit yield of 14% in grafted plants compared to non-grafted plants at 60% ETc level (Al-Harbi et al., 2017). The significant improvement in WUE in tomato plants grafted onto Beaufort and Multifort was reported by Djidonou et al. (2013). The increased level of WUE in grafted tomato plants was 29% and 32% over non-grafted plants under 50% and 100% irrigation regimes, respectively. According to Altunlu and Gul (2012) and Suchoff et al. (2017), the improved performance of tomato plants grafted onto rootstock "Beaufort" was related to improved osmoregulation as indicated by increased leaf proline and relative water content of grafted plants under water stress. Compared to non-grafted plants, grafted tomato showed higher WUE under both drip (6%) as well as furrow (18.7%) irrigation, even when they received similar amount of water in respective irrigation systems (Semiz and Yurtseven, 2010). The grafting effect was less pronounced in drip irrigation probably due to maintenance of water status in soil and plants under continuous water supply in drip compared to furrow irrigation that experienced fluctuation in water status (Semiz and Yurtseven, 2010). In general, low fruit yield in normal (non-grafted) plants under water stress condition could be associated with the reduced plant water status coupled with poor root system (Lee,

1994).

5.3. Mulching

The application of polyethylene mulch in vegetable production was reported to have manifold advantages but most importantly was related to improvement of hydrothermal regimes of soils (Ashworth and Hurrison, 1983). Among the different combinations of deficit irrigation with mulching, the highest WUE of tomato (592 kg/ha/mm) was observed in DI of 50% ETc with polyethylene mulch which has an explicit role of better utilization of water and nutrient, and excellent soil-water-plant relationship (Biswas et al., 2015). In another study, Singh et al. (2009) also found that deficit irrigation at 80% ETc coupled with polyethylene mulch gave the highest WUE of 1.23 t/ha-cm was attributed to reduced nutrient losses due to weed control and improved hydrothermal regimes of soil. Raina et al. (1999) noted that the rate of evaporation under mulching with DI was much lower compared to unmulched treatment which led to higher WUE in tomato. Thus, it is clear that the mulching under DI can further enhance WUE in tomato by inhibiting weed growth, reducing evaporation losses, increasing water and nutrient uptake.

6. Conclusion and future prospects

Based on the scientific literature reviewed in this review, it is inferred that DI is a promising strategy of economizing water use in tomato with providing sustained yield and improved fruit nutritional quality. Application of DI at certain growth stages (e.g., vegetative, fruit ripening) and/ or regulated deficit (eg., 0.8 ETc) and alternatively partial root drying is highly advantageous in term of water saving as well as obtaining satisfactory yield level. However, these agronomical responses under DI may incur due to altered physio-biochemical plant processes which are highly dependent on intensity and duration of DI, stage of growth and climate of the location, besides characteristics of the species/cultivar can also influence significantly to this.

The positive response of DI could be further improved by integrating with other possible interventions namely mulching, growth promoting substances and organisms, hydrogels, sub-surface drip irrigation, anti-transpirants, exploiting the benefit of robust rootstocks by grafting and so on which have been scarcely studied. Hence, future work is warranted to study the interactive effects of such potential applications to make DI a highly sustainable practice in wider perspectives and not only limit to the water saving.

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